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Building integrated energy storage opportunities in China

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ABSTRACT

China has a big population and all countryside are being urbanized recently, more and more buildings are being built with careful considerations of energy saving. Building integrated energy systems are thought to be of priority importance. There are extended energy storage researches and developments for buildings, such as building materials for stabilization of room temperature using the daily and night temperature difference in north China, desiccant materials integrated with buildings used for constant relative humidity control in south China. Solar thermal energy storage using specialized design of hot water tank, phase change materials (PCMs) or pebble stones have been well studied and demonstrated, whereas chemical energy storage capability had been also considered with potential applications. The development of electric battery storage for Photovoltaic (PV) is also highlighted as it is a good opportunity for smart grid development. In modern commercial building, uninterruptible power supplies using rechargeable battery packs and thermal energy storage are currently two of the most common applications for energy storage, while other storage technologies are still at the research stage. The above development of building integrated energy storage opportunities in China are described and analyzed, some demonstration projects are shown in this paper.

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1. Introduction

The energy, derived from fossil sources could not provide a sustainable development for human. Population increasing and blooming urbanization in China lead to a sharply increasing energy demand for buildings. It is well known that China has the biggest building area in the world and the number comes to almost 40 billion m^2 in 2004, while more than 55 billion m^2 until 2010. Energy storage systems become more and more important to balance the difference and reduce the mismatch between supply and demand, especially for new buildings. Different energy storage technologies and products are essential for reducing dependency and pollution of the fossil fuels and making the energy utilization much more efficiently.

In latest three decades, several reviews have appeared on this topic covered many aspects of energy storage technologies. Especially in this decade, many researchers have focused on materials like phase change materials (PCMs), liquid desiccants, novel sensible energy storage materials, thermochemical materials and hygroscopic materials or humidity-controlling materials for building.

Abhat [1] gave a useful and clear classification of materials for thermal energy storage early in 1983. He reviewed materials for low temperature latent heat storage (LHS) in the temperature range 0–120 °C. Then in 1989, Hollands and Lightstone [2] reviewed the state of the art in using low collector flow rates and by taking measures to ensure the water in the storage tank remains stratified. Hasnain [3] reviewed available thermal energy storage technologies, including their individual pros and cons for space and water heating application in 1998. Zalba et al. [4] published a solid–liquid phase change materials review and they listed over about 200 materials in great detailed, both in research and commercially available. Moreover, Farid has published two reviews [5,6], one focusing on building applications and the other discussing PCMs, encapsulation and applications.

From 2007 to 2011, several reviews [7–17] have been published on the basis of predecessors' researches. Some reviews summarized various possible methods for heating and cooling in buildings integrated energy storage [5,6,8,15]. Cabeza [12] summed up the latest literatures on the use of PCMs in buildings, which included almost all materials suitable for buildings, and also compiled information about the technology requirements, classification of materials, various materials available and problems and possible solutions on the application in buildings. Lately, Wang et al. [18] reviewed the development of various energy systems related to residential refrigeration, power generation and storage.

Though the sensible thermal storage has the advantages of high reliability, simpler structure and operation compared with the latent storage, the energy storage density always is low and few reviews [19,20] focused on sensible energy storage and sensible thermal materials like water or pebbles. Han et al. [19] did an overview of various designs of thermal stratification tanks and summed up different models for modeling analysis, while the influencing factors were carefully considered and the energy efficiency of water tank was outlined. The other paper, written by Singh et al. [20], summarized various packed bed energy storage studies both analytically and experimentally, including different types of packed beds, various materials, heat transfer enhancement in packed bed, and pressure drop through packed beds, while it is concluded that rocks and pebbles as packing materials are used in most studies. The most popular heating system Chinese kang in north China is also known as a kind of sensible energy storage application. Zhang et al. [21] reviewed the basic heat transfer and airflow principles of Chinese kang and the thermal performance, however, in another paper [22] he paid more attention on the thermal storage performance by continuous or intermittent firings.

Thermochemical energy storage (TCES), as another way of thermal energy storage technologies, uses reversible chemical reactions to store thermal energy in chemical bonds by supplying thermal energy. Chemical sorption reaction, included adsorption and absorption, with advantages of high storage density, may be a promising way of energy storage combined with a solar collector system in the future. Seldom work of TCES was released applied with buildings, since the safety and mature of this technology are still to be considered. However, Lovegrove et al. [23] operated the world-first solar-driven ammonia-based TCES system successfully in Australian National University in 1998 and following the installation for 15 kW_{sol} receiver, 10 kW_{chem} synthesis reactor an various improvements to the closed-loop experimental system, a continuous 24 h run of solar ammonia storage and heat recovery was performed in 2002 [24].

Nowadays, there are other energy storage systems blooming, which can also be integrated with building, such as desiccant system and solar cell system. With the advantages of handling sensible and latent heat loads independently without using CFCs or HCFCs, the desiccant air conditioning technology developed rapidly and more and more products came to market. Liquid desiccant dehumidification has been proved to be an effective way to extract the moisture of air with renewable energy like solar energy, or relatively less energy consumption compared to the traditional cooling dehumidifying in building application. In addition, energy storage of liquid desiccant system can be realized by storing strong desiccant solution. The strong desiccant salt solution was regenerated by extra thermal energy and has the ability of dehumidification, which can be released when needed. Another way to control the humidity of building is the utilization of hygroscopic building materials as a passive way.

In a PV power system, battery packs play an important role for storage and power control. During the day the solar cells convert solar energy into electric power, part of which is provided directly to the loads while the extra to charge the storage battery. For Building integrated photovoltaic (BIPV) system, the electrical

storage methods include two types, one is the solar battery integrated with the building, which can storage the excess energy and provide a stable output during the night or cloudy days, and the other is gird-connected BIPV system, which can storage the extra electric energy into the municipal grid as an infinitely great and infinite cycle life battery.

The application of energy storage is a key emerging frontier for modern commercial buildings. The increasing interests in the opportunity for energy storage applications are driven by the market momentum toward high-energy efficiency commercial buildings, the growth of renewable energy applications like solar energy and wind energy, and the bright prospect of smart grid technologies. Nowadays, the main energy storage applications in modern commercial buildings are thermal energy storage based on time shifting strategies and uninterruptible power supplies (UPS) based on rechargeable battery packs. For example, for a commercial building with data centers, having a backup power has always been an important issue. Furthermore, the renewable energy installations would decrease operation expenses of rechargeable battery, though the initial costs increase. By using thermal energy storage in commercial building, the load shifting provides reliable operation and lower electricity running costs and increases the system output with the additional thermal energy storage. The market for energy storage in modern commercial buildings will achieve rapid development in the next few decades.

This paper presents a review on the energy storage researches and technologies, which can be integrated with building, especially the developments in China. In addition, some commercial cases and research projects have also been presented.

2. Thermal storage materials for building and classification

Thermal energy storage (TES) is one of the most promising and sustainable ways for energy storage in buildings. Energy savings from TES can be obtained in various ways for buildings [25].The energy loads of buildings are affected by climates and human activities and fluctuate in a certain form. By integrated energy storage system, parts of traditional energy consumption can be replaced by sustainable energy, such as waste heat or solar energy. For example, solar energy can be collected and stored during the day while it can be released for space heating or hot water at night. The application of energy storage can also reduce the demand of purchased energy due to the peak and off-peak tariffs, like electric. In China, the off-peak tariffs of electric are only about one third of peak tariffs. So energy storage system can be used to shifted parts of the building energy consumption during the peak period to the valley period. In addition, the equipment sizing of air conditioning for buildings can be reduced due to the energy storage system of shifting loads.

The TES systems applied in buildings can be easily divided into three types, including sensible, latent, and TCES. In sensible TES system, heat is stored by the temperature changing of storage substance, and the amount of heat stored by sensible TES is directly proportional to the temperature difference, the mass and the heat capacity of sensible materials. The sensible TES system are flexible and suitable for both short term and long term storage, such like rock or earth beds, solar ponds and aquifers for long term storage (seasonal), whereas water tanks, rock beds for short term (daily). For latent TES system, the storage relies on the phase change process, while the mainly amount of thermal energy stored in a latent material is directly related on the mass of storage medium and the latent heat of phase changing, usually limited to melting.

The classification of the materials used for TES had been given by Abhat [1] and Mehling and Cabeza [26]. As shown in Fig. 1, the storage materials classification has been given including sensible, latent and chemical heat. In Table 1, parts of frequently-used sensible TES materials and PCMs for building application had been shown including organic, inorganic and their mixtures. A list of some commercial PCMs for thermal storage applied in buildings is given in Table 2. Though PCMs are still in the stage of researching in laboratory and few commercial materials for buildings are available in Chinese market.

3. Sensible heat storage

As the most simple and cheap way to storage energy, sensible heat storage (SHS) has been used for a long time in worldwide. Considering the technological maturity and economic factors, SHS is superior compared with LHS.

3.1. Liquid substance: Water

With the advantages of wide range storage temperature, high thermal capacity, nontoxicity, cheap and easy obtainment, using liquid water as the storage medium is the first choice for domestic solar utilization in China. Hence, water tank is applied in building energy storage system in extremely broad areas, especially for civil use and always placed on roof of buildings. As we all known, water tank plays two vital roles in the energy storage system, one is energy reservoir and the other is redistribution. Building of thermal stratification is the crucial part of water tank design. An obvious temperature gradient in water tank should be formed between the top and the bottom, which is known as stratification.

Yu et al. [30] used the multimode approach to model temperature stratification in water tank, and hourly simulation of a typical solar domestic hot water (SDHW) system during a whole year was carried out. The simulation results indicated that collector efficiency and solar fraction of SDHW system could be significantly increased with the temperature stratification in storage tank. An engineering project was simulated by TRNSYS software to investigate the thermal performance by Han et al. [31]. This project used a novel horizontal water reservoir and was applied in large-scale thermal storage of solar water heating system. Different types of stratified tank volumes and flow rates are considered and compared, and the optimized parameters for solar energy storage tank were suggested.

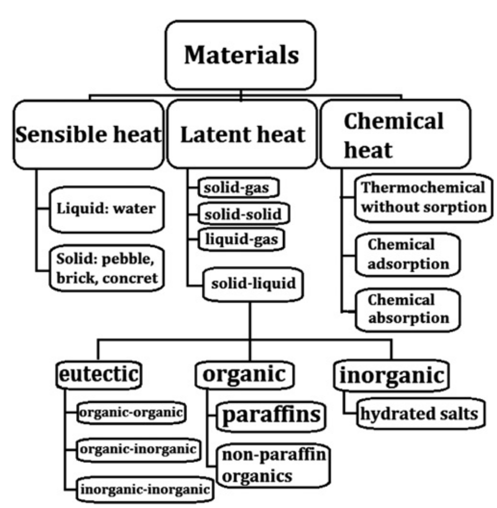

Fig. 1. Classification of materials for TES (revised from [1,4,27]).

Table 1
Properties of commonly used TES materials for building application.

Classification	Typical materials	Temperature ranges/melting temperature (°C)	Latent heat of fusion (kJ/kg)	Density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat (kJ/kg K)	Reference
Sensible heat storage	Pebble	*	*	2500	2.2	0.78	
	Water	0–100	*	1000	0.61 (at 300 K)	4.2	
	Concrete	*	*	2000	2.33	0.88	
PCMs, organic	Paraffin C_{13}–C_{24}	22–24	189	0.760 (liquid) 0.900 (solid)	0.21 (liquid)	*	[4]
	Black paraffin	25–30	150	*	*	*	[28]
	Polyglycol E600	22	127.2	1126 (liquid, 25 °C)	0.1897 (liquid, 38.6 °C)	*	[25]
	Caprylic acid	16.3	149	901 (liquid, 20 °C)	0.149	*	[4,8]
	Paraffin C_{26}	56.3	256	*	*	*	[8]
PCMs, inorganic	$Na_2SO_2 \cdot 10H_2O$	32	251	1485 (solid)	0.854 (solid)	*	[15]
	$CaCl_2 \cdot 6H_2O$	29.7	190.8	1710	0.540–1.088 (liquid–solid)	*	[4,15]
	$Mn(NO_3) \cdot 6H_2O$	25.5	125.9	1738 (liquid, 20 °C)	*	*	[8,15]
	$Na(CH_3COO)\ 3H_2O$	58	226–264	1280 (liquid)	0.63	*	[4]
PCMs, eutectic	Capric acid–Lauric acid 45/55	21	143		*	*	[4]
	$CaCl_2$–NaCl–KCl–H_2O 48/4.3/0.4/47.3	27	188	1530 (liquid) 1640 (solid)	*	*	[26]
	Palmitic acid–Stearic acid–other fatty acids 27.5/65/7.5	51–56	180	*	*	*	[29]

* means no data available for this parameter in the reference.

Table 2
Typical commercial PCMs manufacturers and properties of their products.

PCMs Name	Classification	Melting temperature (°C)	Heat of fusion (kJ/kg)	Manufacturer	References
RT 20	Paraffin	22	172	Rubitherm GmBH	www.rubitherm.de
ClimSel C24	Salt hydrate	24	108	Climator	www.climator.com
S 27	Salt hydrate	27	207	Cristopia	www.cristopia.com
TH 29	Salt hydrate	29	188	TEAP	www.teappcm.com
RT 32	Paraffin	31	130	Rubitherm GmBH	www.rubitherm.de
RT 55	Paraffin	55	172	Rubitherm GmBH	www.rubitherm.de
ClimSel C58	Salt hydrate	58	259	Climator	www.climator.com

As shown in Fig. 2, Han et al. [19,32] introduced a novel design of horizontally partitioned tank, which can be applied in large-scale solar energy system. The partitioned tank can be placed in a limited space on the roof or in the basement of the building. The experimental results showed that this kind of water tank had good performance not only on energy storage but also on building thermal stratification both in each chamber and the whole tank. For each chamber along the horizontal partition, the temperature decline can be kept at 15–20 °C while the total temperature difference of the inlet and outlet of the tank is about 70 °C. They concluded that partitioned tank could effectively inhabit transverse heat transfer, so it can be a good choice in a small room like attic or basement.

Modeling analysis is another important content to study the thermal stratification in the tank and many researchers have devoted great attention on modeling analysis. The stratification performances were influenced by geometrical structure and operation condition. The geometrical factors [33,34] of tank included water tank size, the aspect ratio, baffle shape and inlet shape of diffuser system in tank. Comparing 12 different baffle plates to no obstacle case by numerical and experimental methods, the results showed placing obstacle in tank can obtain better thermal stratification. It is obvious that the obstacle types having gap in the center have better performance on thermal stratification than those having gap near the tank wall [35]. As shown in Fig. 3, these two types of obstacle baffle can provided higher thermo-cline than other cases and further studies showed the cone plate obstacle had a better performance of stratification than the other one.

Though solar water heater systems have the advantages of mature, simple operation, and wildly used in the lives of millions of people in most countries, the bottlenecks of this solar conversion technology includes low efficiency of heat storage, costs of auxiliary equipments, drop location and so on. Nevertheless, solar water heat storage systems have demonstrated the feasibility of utilization of building integrated solar energy.

3.2. Solar water heating storage combined PCMs

In the solar water heater system, the temperature of water changes during storing or releasing processes, while in LHS the temperature of storage medium is much stable. The successful application of solar water heating storage system depends on the way of energy storage used. By adding PCM component, as a thermal barrier in a solar water system, it is obvious that the system volume will decrease significantly compared to traditional water systems only use water and both the heat storage temperature and the supply temperature can be maintained in a narrow range around the phase change temperature of the PCM.

For civil utilizations in residential, commercial or industrial buildings, the required temperature of hot water is around 60 °C, whereas it is about 50 °C for bathing, laundry and cleaning operations [37]. Therefore, PCMs with phase change temperature

ranges from 50 to 60 °C can be employed in the SDHW system, as shown in Tables 1 and 2.

Based on some previous researches [38,39], Hasan et al. [40] investigated some organic PCMs applied in SDHW system and they concluded that myristic acid, palmitic acid and stearic acid, whose melting temperature ranged from 50 to 70 °C, are the most promising PCMs, though some degradation happened after normal heating cycles (20–80 °C) and severe cycles (20–150 °C).

As shown in Fig. 4, Rabin et al. [41] carried out an integrated solar collector storage system. The storage medium was salt hydrate and the melting temperature of the eutectic mixture ranged from 27 to 29 °C and the latent heat of fusion was 164 kJ/kg.

Tarhan et al. [42] designed and tested three trapezoidal built in storage solar water heaters to find the characteristics of the added PCM and the results showed that myristic acid performed better than lauric acid when maintained the water temperatures since its phase changed at 51–52 °C and acted as a thermal barrier. Meanwhile, Cabeza et al. [43] also showed that it is a promising way to add a PCM module in water tanks as shown in Fig. 5. A granular PCM–graphite compound with 90 vol% of sodium acetate trihydrate and 10 vol% graphite was employed and the performances of different numbers of PCM modules were compared. With six modules of 6.3 kg PCM for each and 9 L in volume, the energy density increased about 66.7% with 1 °C temperature difference, and 16.4% with 8 °C temperature difference. Mazman et al. [44] extended Cabeza's researches on PCM/graphite composite with optimized thermal properties. Their results showed that paraffin-stearic acid gave the best performance of thermal enhancement of the SDHW tank (74% efficiency).

Nallusamy et al. [45] developed a TES system for the use of SDHW applications at an average temperature of 45 °C using combined latent and sensible heat storage method, and had a better performance compared with the traditional SHS, where paraffin was used as PCM with a phase change temperature around 60 °C.

By adding a PCM module to the tank, energy storage density increases. There will be a delay in achieving thermal equilibrium and heat can be stored for a longer time at the upper part, which has the same effects like thermal stratification in water tank. During the discharging stage, the PCM releases its latent heat to cold water and hot water will be available for even longer durations. However, the combined system has disadvantages of performance degradation, investment increasing and complication compared with the tradition SHS, and as a result few engineering projects were reported.

3.3. Solid substance: Pebble, concrete and soils

Solid substance like pebble, concrete and soils are also used in heat storage. Energy storage based on these materials provide advantages such as non-toxic, non-flammable and cheap, though compared to water or PCMs the energy storage density is lower. These solid substances usually used both as heat transfer surface and storage medium.

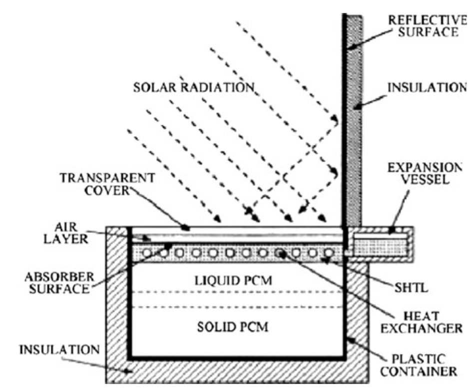

Fig. 4. Schematic of the integrated storage system [41].

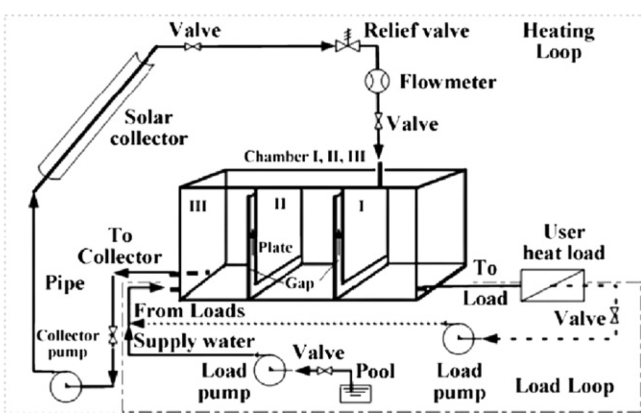

Fig. 2. Schematic of horizontally partitioned water tank system [19].

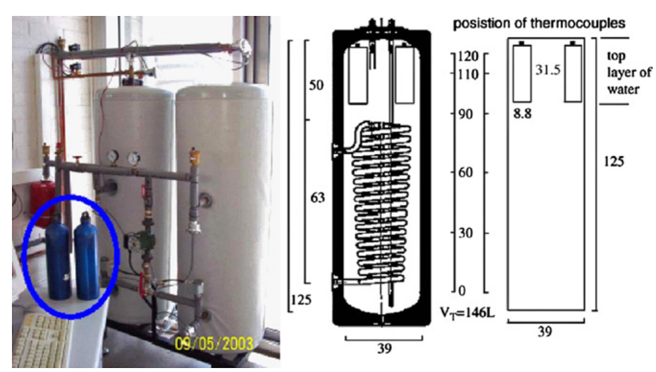

Fig. 5. Hot-water tanks from Lapesa and PCM modules [43].

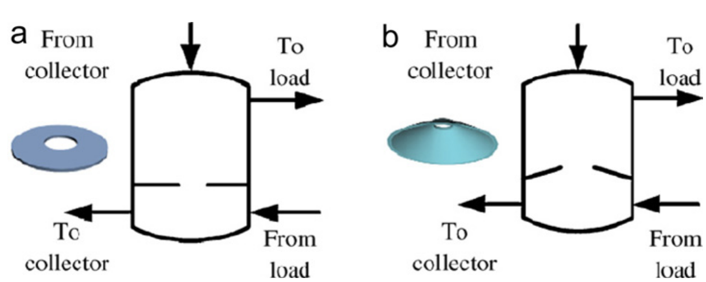

Fig. 3. Design comparison between the flat plate obstacle (a) and cone plate obstacle (b) [36].

Laing et al. [46] had integrated sensible heat storage modules into parabolic trough power plants (as shown in Fig. 6) and the testing results concluded that high temperature concrete is more favorable than castable ceramic. However, for buildings, the packed beds are commonly used for the thermal energy storage for space heating. A packed bed storage system usually consists of packed solid storage medium through which the heat transport fluid (water or air) is circulated. Packed beds, always is a volume of porous media obtained by packing particles like pebble stones or sands into a container, are the crucial part of the whole system.

A number of both analytical and experimental studies focused on packed beds were reported, including the system design, storage materials and various methods on heat transfer enhancement, but there are few applied cases. Fig. 7 shows the mostly commonly used storage system for solar heating. Usually in a packed bed system, the air played as heat transport fluid flowing from solar collectors into a bed and thermal energy is transferred to the solid medium during the charging phase. Zhao et al. [47,48] had designed a solar heating system including pebble bed and heat storage tank as heating storage parts. The system was used to heat a 3320 m^2 indoor area in Qinhuangdao in North China and it was the first large scale practical solar air heating system in China. A model based TRNSYS environment had been established and the design parameters were optimized to achieve a higher solar fraction. The design of air-based solar heating system with storage was shown in Fig. 8.

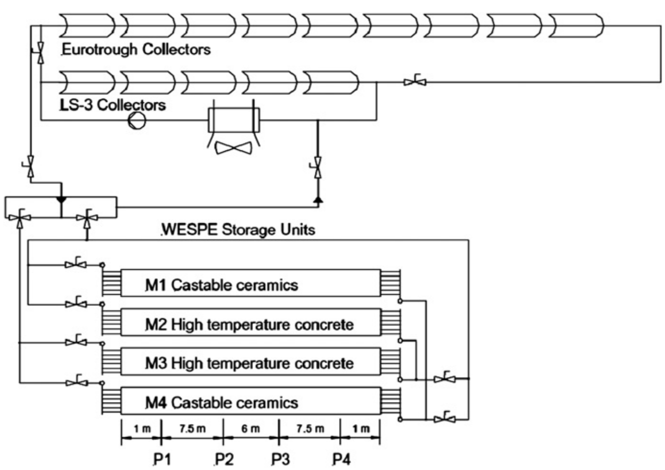

Fig. 6. Integration of storage modules into parabolic trough test loop [46].

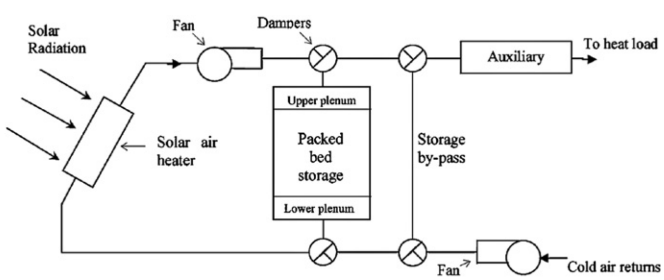

Fig. 7. Schematic diagram of a most commonly used packed bed storage system [20].

The soil can serve as heat sink for buildings in regions with very cold winter and the natural soil temperature in later summer is low. Zheng et al. [49] developed the experiment system for standing cooling storage using deep soil and studied the change of cool storage rate and temperature field of soil in severe cold region. They verified the availability of soil and explored different operation mode of improving cool storage performance.

3.4. Chinese kang

In China, heating for rural buildings consumed 25% total building energy consumption [50]. Chinese kangs (as shown in Fig. 9) are widely used as a rural domestic heating system in Northern China for more than 175 million people [21]. As the most ancient heating system in cold regions in China, the kang integrates natural ventilation and thermal mass into one system. With well thermal storage design, the kang can performs better and keep indoor air temperature stable at the time without firing. Moreover, suitable thermal storage design can improve occupants' thermal comfort level while less biomass materials are needed. Similar heating systems also existed in other countries, such as the ondol (heated floor) in Korea [51], and hypocaust developed by Romans [52].

An elevated kang has been popular these years, however, seldom analytical and experimental researches had been investigated. Zhuang et al. [22] studied the performance of the elevated kang under different firings strategies by developing a thermal and airflow model. Some critical parameters, which affect the fluctuations of kang plate temperature and indoor air temperature, have been identified. Obviously, after adding the firings, all the temperatures increase quickly until reaching the maximums. As shown in Fig. 10, without firings the temperatures decrease gradually until the next firings come.

Based on their previous work, Zhuang [53] had given an elaborate analysis on the thermal storage characteristics of the coupling between thermal pressure flow and mass of kang. Based on field measurement and questionnaires, Chen et al. [54] studied the indoor thermal environment and the TES performance of rural residences in a coupled heating pattern of passive solar-collected wall and oven-kang combination. The results indicated that the performance of the coupled heating pattern is superior to that of single kang pattern, and that the former could save coal for

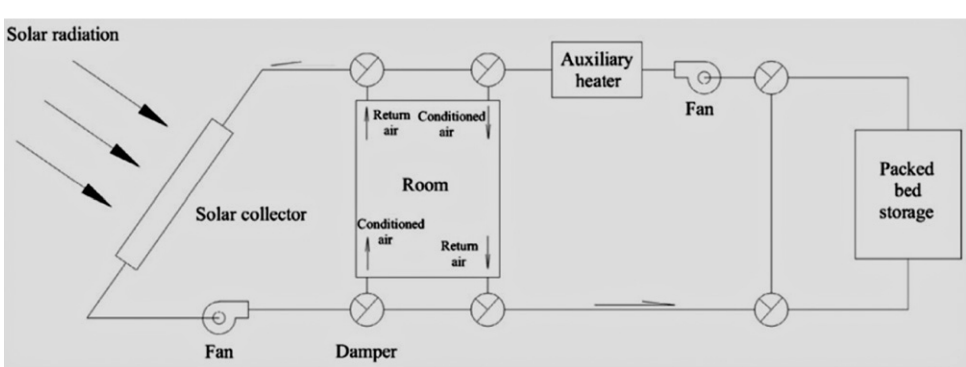

Fig. 8. Schematic diagram of air-based solar heating system with packed bed storage [47].

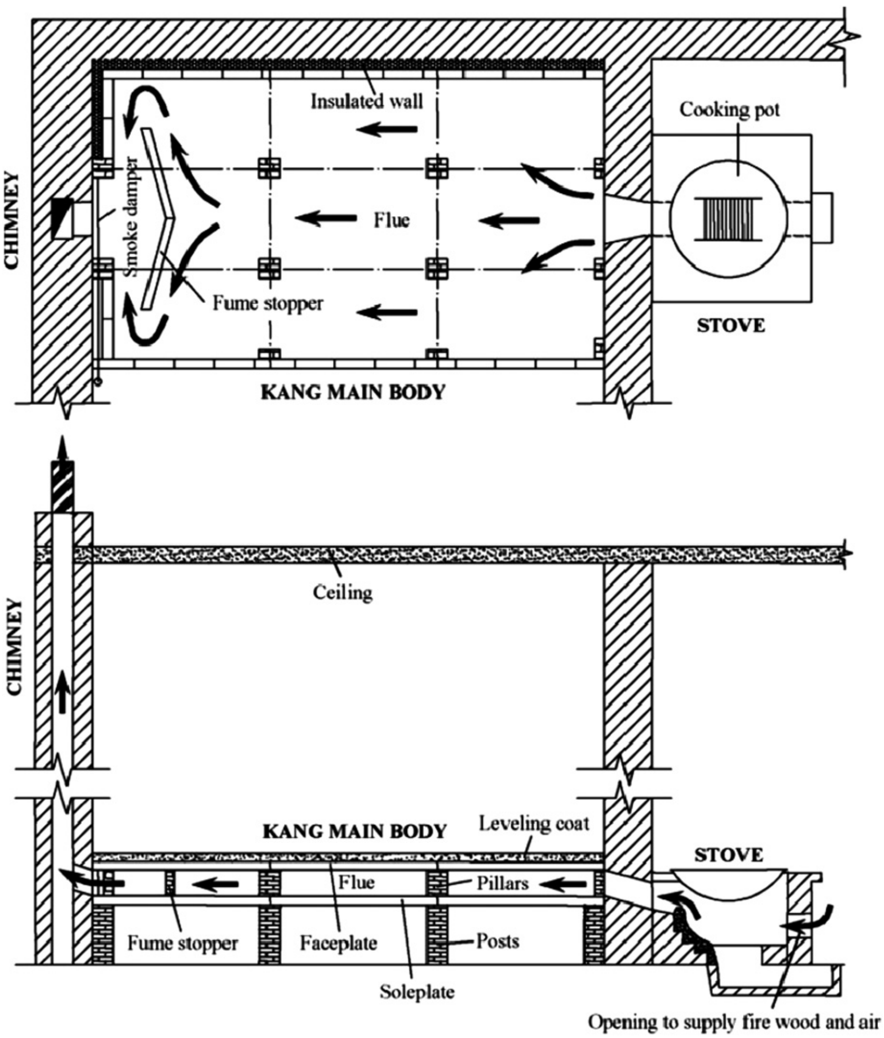

Fig. 9. An illustration of the elevated kang system including the chimney, the kang body and stove [21].

heating by about 50% while its initial investment increased by only 10%.

4. Latent heat storage with PCMs

Compared to the SHS system, the LHS provides advantages of much higher storage density and a smaller temperature variation during the processes of charging and discharging. There are various PCMs for LHS with different properties, making them attractive for the applications in buildings. Generally speaking, there are two different purposes for the applications of PCMs in buildings, one is using free energy for heating or cooling like solar energy or night cold while the other is using manmade energy sources, like electricity with different tariffs [15].

4.1. PCM applications in building envelopes

The concepts of different methods of PCM application in buildings are shown in Fig. 11 [16], including passive solar heating and night cooling. PCMs can be integrated with almost every part of building envelope, such as PCM wall, PCM floor, PCM ceiling and PCM window.

As shown in previous Tables 1 and 2, some of PCMs melting points range from 18 to 28 °C, which are just in the human comfort temperature range. However, for suitable applications of PCM in buildings, there are still some other factors needed to be considered, like compatibility with building material, stability under time after time charging and discharging and flammability etc.

4.1.1. Experimental and numerical studies on PCM floor

Seldom experiments on PCM floor have been reported, though there are a lot of literatures studied by numerical method. Lin et al. [55] carried out a novel under-floor electric heating system with shape-stabilized PCM plates, as shown in Fig. 12. The experimental results showed that the PCM floor provides a good economic feasibility and more than half of the total electric heat energy for the experimental building can be shifted from the peak period to the off-peak period. Considering the peak and valley periods of electricity tariffs in China, it makes a significant benefit of application. The experimental data also can be used to verify the feasibility and accuracy of numerical model.

In the follow-up work [56], they undertook a model to study the storage performance of the same heating system and concluded that the storage system could be applied in different climates under a good design. In another paper [57], they proposed a kind of novel electrical floor heating system with ductless air supply using shape-stabilized PCM for thermal storage in order to overcome the shortcomings of the passive under-floor electric heating system with thermal storage.

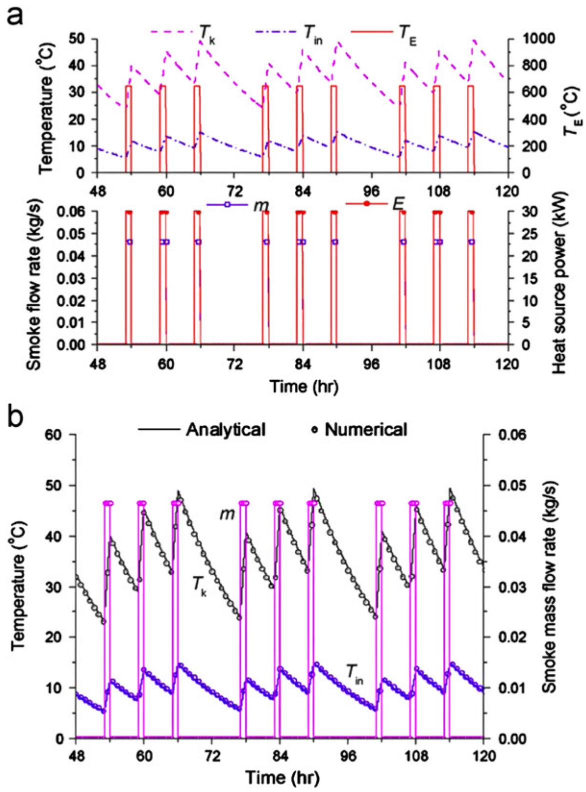

Fig. 10. (a) The results of a solution on the base kang when the heat source power is intermittent and (b) comparison of the kang plate temperature and indoor air temperature solved by both numerical and analytical methods, respectively, when the heat source power is intermittent [22].

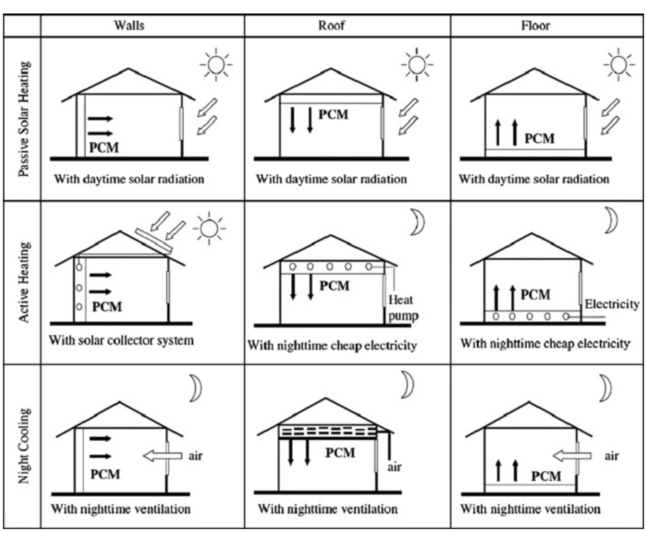

Fig. 11. Various forms of PCMs application for building envelope and different operation strategies [16].

Li et al. [58] proposed a novel form-stable phase change material, which consist of micro-encapsulated paraffin high density polyethylene/wood flour composite as the supporting materials. They conduct simulation researches on the performance of the temperature regulating under the condition of the compound material as the thermal storage layer by the validated model. The results indicated this material was promising, while the cost–benefit analysis was also included.

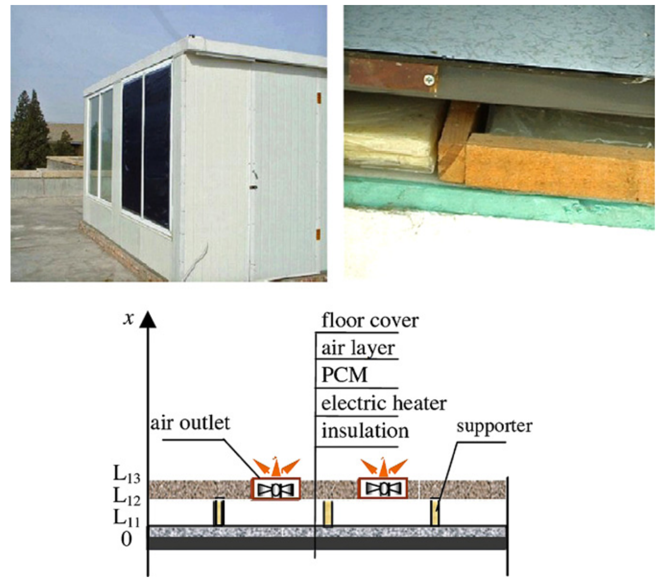

Fig. 12. The experimental house and schematic of heating system [55].

Jin and Zhang [59] proposed a novel double layer PCM floor (as shown in Fig. 13), which contained two layers of different PCM with different phase change temperature, to store heat or cold energy, respectively, in the valley period. The numerical analysis revealed that the optimal phase change temperature of PCM for heating and cooling in this system were 38 and 18 °C. Assuming the heat of fusion for both two kinds of PCM was 150 kJ/kg, the PCM floor could release extra 41.1 and 37.9% of energy during the heating and cooling process compared to the system without PCMs.

4.1.2. Researches on some other kinds of envelopes

A simplified theoretical model had been built by Xiao et al. [60] to optimize an interior PCM as inner linings of building including wall, ceiling and floor in a lightweight passive solar room. By the analytical study, they concluded that the interior PCM for energy storage has little effect on average indoor air temperature and the amplitude decrease with the increase of the product of surface heat transfer coefficient and surface area of the PCM panels.

Trombe wall as a kind of sensible energy storage system can be used for buildings with winter heating by suitable design. Unlike traditionally trombe walls depend on SHS, the concept of the PCM trombe wall is more attractive and can provide greater heat storage density. However, the concept is still awaiting successful implementation, and few researches [61–63] focused on this topic.

Night ventilation is a good way for improving thermal comfort of indoor environment. When it integrated with PCMs, there are many advantages. By cooling the fabric of the building integrated with PCMs in this way, the PCMs can store extra cooling for providing a lower mean radiant temperature of the space during the following day. It not only provides a good opportunity for saving energy, but also to some extent improves the human thermal comfort.

Kang et al. [64] presented a new design of passive cooling system, as shown in Fig. 14. Two thousand capsules containing 150 kg PCM (fatty acid developed by their own) were used and hung under the ceiling. They concluded that the thermal comfort level had been improved significantly under both numerical and

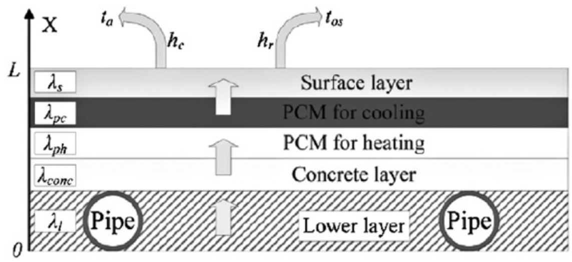

Fig. 13. Layout of the double layer PCM floor [59].

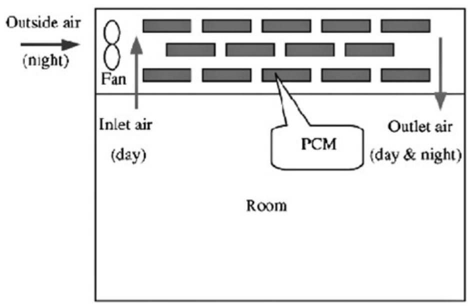

Fig. 14. Schematic of a novel passive cooling system [64].

experimental results and this system is promising in the application of energy-efficient buildings.

Ismail and Henriquez [65,66] did an interesting work on tying to use a kind of PCM window to reduce the solar gain for improving the indoor thermal comfort. The design of the double glass PCM window was shown in Fig. 15. It is formed of a double glass window, separated by a gap of certain width, filled with a PCM like a hamburger. They summed up that the PCM filled glass window system is viable and thermally effective and the proposed model and numerical predictions are validated by experimental results.

4.2. Model researches for packed bed latent heat thermal energy storage system

Many researchers have spent their efforts on mathematical models for studying the thermal and hydrodynamic characteristics of packed bed in latent heat thermal energy storage (LHTES) system, though many models failed to consider the thermal gradients in the PCM spheres and the effect of the heat transfer and the fluid flow due to the geometrical features of the PCM spheres.

Erek and Dincer [67] conduct a numerical research by using the concentric dispersion model based on the empirical heat transfer coefficient correlation for studying the heat transfer performance of a TES system. Arkar and Medved [68] and Benmansour et al. [69] both applied the continuous solid phase model to investigated the thermal response of thermal property of PCM in LHTES systems. Seeniraj and Narasimhan [70] also used a continuous solid phase model to analyze the influence of various parameters, including Stefan number, Stanton number and porosity on temperature.

Xia et al. [71] developed an effective packed bed model to investigate the flow field as the fluid flows through the voids of PCM and account for the thermal gradients inside the PCM spheres simultaneously. A parametric study have been conducted on the influence of the arrangement of the PCM spheres and encapsulation of PCM on the heat transfer performance of LHTES bed by the proposed model, which was hard to perform by other packed bed models mentioned before. They made a conclusion

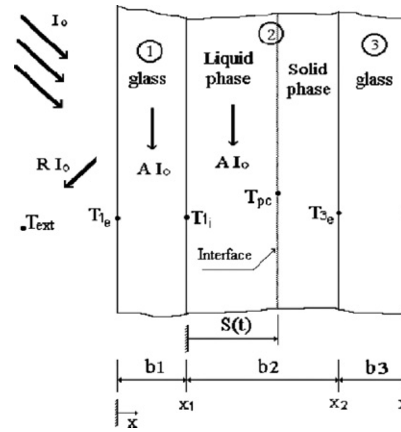

Fig. 15. Layout of the double glass window with PCM [66].

that the performance of random packing is much better than special packing for heat storage and retrieval.

A series of modeling studies about thermal characteristics of different types LHTES systems have been took by Kang et al. [72], Zhu et al. [73] and Zhang et al. [74]. The method they used is called the alternative iteration between temperature and thermal resistance method. Based on this model, they all analyzed the thermal performance and heat transfer characteristics of PCM sphere packed bed.

4.3. Material researches on PCM

There are some unfavorable properties of PCMs like low heat conductivity and phase changing during charging process, resulting in limitation of application in building. Many researchers focused on the improvement of PCM with some additives.

4.3.1. Properties of composite materials

Li et al. [75] reported the TES materials of *n*-nonadecane/cement composites and the testing results showed that the composites melt at temperature of 31.86 °C with a latent heat of 69.12 kJ/kg and solidify at temperature of 31.82 °C with a latent heat of 64.07 kJ/kg when the mass percentage of *n*-nonadecane in the composites is 50%. Xia and Zhang [76] used the expanded graphite (EG) to improve the heat transfer performance of PCM. Their experimental results showed that composite PCM (acetamide (90)/EG (10)) achieved about five times increase in thermal conductivity compared to the pure acetamide, and the durations of charging and discharging processes decreased sharply.

Paraffin, as one of the most preferred PCMs, has a disadvantage of low thermal conductivity, to a large extent, limits its utilization. Xiao et al. [77] developed a composite PCM consist of EG, styrene–butadiene–styrene (SBS) triblock copolymer as supporting material and paraffin. They measured the heat of fusion and melting point of the composite by a differential scanning calorimeter and the results showed a high thermal conductivity and nearly 80% of the latent heat of fusion per unit mass of the paraffin. Xia et al. [78] prepared and characterized EG/paraffin composite PCMs to improve the heat transfer performance of paraffin, varying the mass fraction of EG from 0 to 10 wt%. This paper showed similar results as mentioned before [76] and due to the higher thermal conductivity the heat storage/retrieval durations for paraffin (90)/EG (10) composite were reduced by 48.9 and 66.5%, respectively, compared to pure paraffin.

4.3.2. Shape-stabilized phase change material

As shown in Fig. 16, the shape-stabilized PCM (SSPCM) as a kind of novel compound has been attracting a lot of researchers' interests. Usually, it consisted of dispersed PCM and supporting materials, like paraffin and high density polyethylene (HDPE).

Inaba and Tu [79] did some pioneer work on thermophysical properties and measuring methods of SSPCM. Ye and Ge [80] revealed that no matter whether the PCM was solid or liquid, the SSPCM can keep its shape when the operating temperature was under the melting point of the supporting material. Therefore, the SSPCM can be applied in different buildings envelopes without encapsulation due to the less possibility of leakage. In addition, Xiao et al. [77,81] improved the thermal conductivity of paraffin by combined with expanded graphite.

Except the experiments mentioned before [55,57], Xu et al. [83] and Zhou et al. [84–88] did a series of numerical studies on the SSPCM. Xu et al. [83] developed a model and analyzed the influence of various factors including the thermal conductivity of the PCM, the heat of fusion, the melting temperature, and so on. A serial of experimental results verified the model.

Zhou et al. [84] studied the performance of a heating storage system using SSPCM plate as inner linings of building envelope by TRANSYS. The simulation results indicated that the indoor thermal comfort level was improved and 12% heating energy consumption was saved in winter in Beijing by the effect of SSPCM plates. In another paper [88], the performance of night ventilation was added. The results indicated that the indoor thermal comfort has been improved and about 76% of daytime energy consumption has been saved compared to the system without SSPCM and night ventilation.

5. Thermochemical energy storage opportunity

TCES depends on chemical reactions and the thermal energy can be storage by chemical binds. The chemical reactions involved must be completely reversible, and sorption reactions can be of priority considered. As shown in Fig. 17, compared to sensible or latent heat storage materials, materials used in sorption storage have higher storage density, so the volume of storage component will be smallest to store the same amount of energy.

Generally, sorption reaction includes both absorption and adsorption. In early days researchers focused on adsorption heat

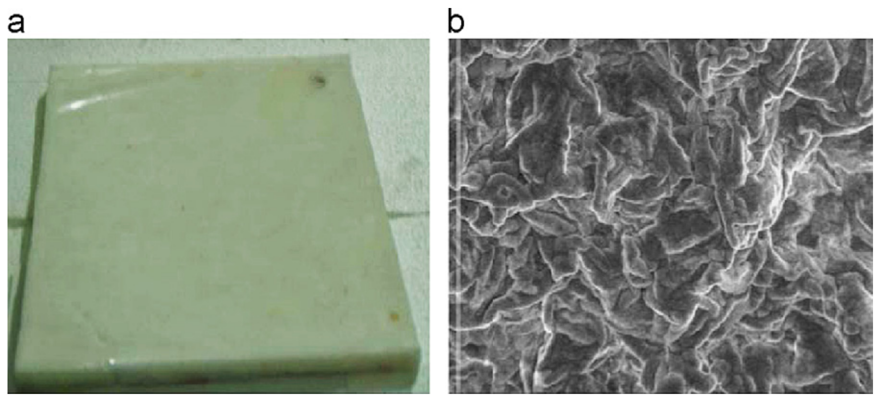

Fig. 16. Photo (a) and electronic microscopic picture by SEM (b) of a shape-stabilized PCM plate developed by Zhang et al. [82].

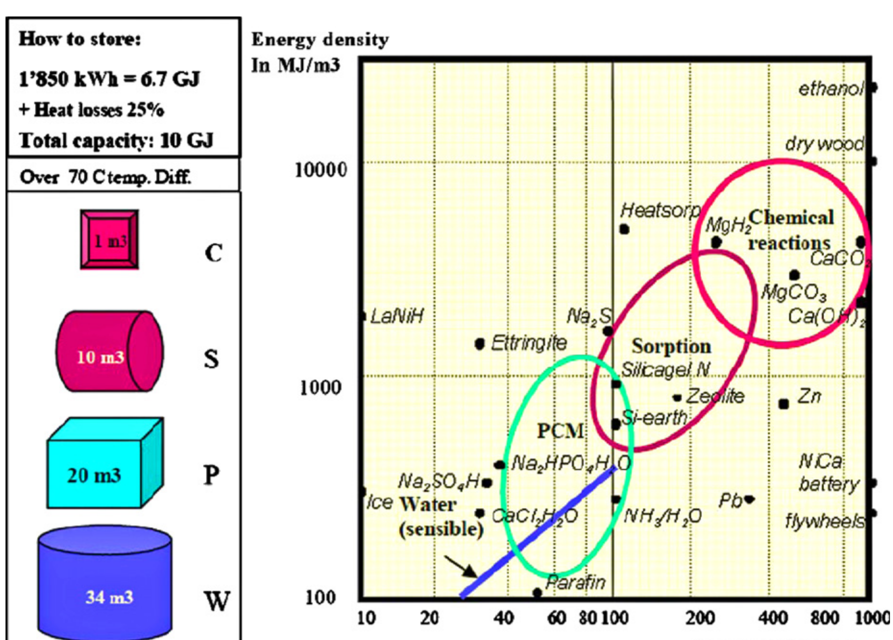

Fig. 17. Energy density of high-energy storage methods [27].

storage, however, adsorption cold storage has attracted much more attention nowadays and become much more promising.

The integrated energy storage and energy upgrade of low-grade thermal energy based on the thermochemical pressure-down desorption process and temperature-lift adsorption process was studied by Tingxian [89]. Based on the theoretical results, the working temperature of low-grade thermal energy can be upgraded from 87 to 171 °C using a group of sorption working pair $MnCl_2$–$CaCl_2$–NH_3 (as shown in Fig. 18). Moreover, the proposed method can give the flexibility of deciding the margin of upgrade temperature by choosing appropriate sorption working pairs. Compared with the conventional energy storage system, the chemical storage system has distinct advantages of higher energy storage density (as shown in Table 3), combined heating and cooling supply, integrated energy storage and energy upgrade using the same sorption system. However, the problems of high pressure and tightness still need be carefully considered if this system is aimed to apply in commercial building.

It is noteworthy that a series researches about the ammonia-based thermochemical storage system were conducted by Lovegrove et al. [23,24,91,92] in Australian National University. It has been shown that this kind of thermochemical storage, which is based on the reversible dissociation of ammonia, for concentrating solar power is technically achievable and development has largely centered on use with dish concentrators, of which a 489 m^2 prototype is now available.

Though thermochemical energy storage has a high storage energy density, seldom application was reported for buildings, since many challenges still need to be solved including safety, tightness, corrosivity, system efficiency, cost of components and long-term stability. After breaking through these bottlenecks, this kind of thermochemical storage might be much more promising and significant on economic benefit.

6. Desiccant material for building humidity control

6.1. Liquid desiccant system with energy storage for building

Indoor humidity, as one of the most important parameters in indoor thermal comfort, affects skin humidity and perceived indoor air quality, and even sensible and latent conduction loads. Liquid desiccant can be classified as absorption reaction and the most commonly used materials are LiBr, LiCl, $CaCl_2$ and triethylene glycol. In China, there is not only a lot of literature on the liquid desiccant system reported by universities and institutes,

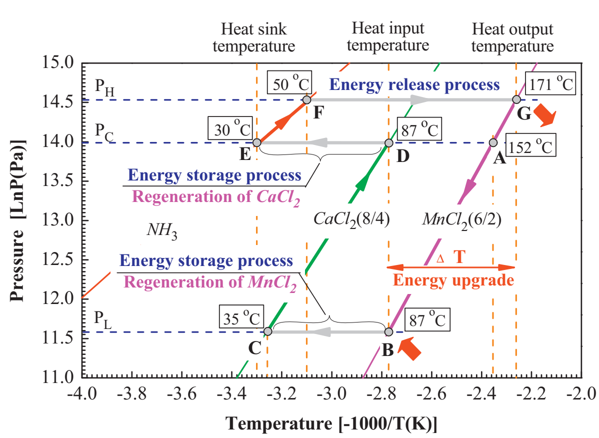

Fig. 18. Theoretical Clapeyron diagram of the thermochemical sorption energy storage and energy upgrade process using a group of sorption working pair $MnCl_2$–$CaCl_2$–NH_3 [89].

Table 3
Performance analysis of integrated energy storage and energy upgrade of low-grade thermal energy using different sorption working pairs [89,90].

Reaction salt	Reaction enthalpy (J/mol)	Reaction entropy (J/(mol K))	Coefficient *m*	Coefficient *n*	Molar mass (g/mol)	Energy storage density (kJ/kg)
NH_4Cl	29,433	207.9	3	0	53.4	1653.5
NaBr	35,363	225.2	5.25	0	102.9	1804.2
$BaCl_2$	38,250	232.4	8	0	208.2	1470.2
LiCl	36,828	224.6	1	3	42.3	870.6
$CaCl_2$	41,013	230.1	4	4	110.8	1480.6
$CaCl_2$	42,269	229.7	2	2	110.8	763.0
$MnCl_2$	47,416	227.9	4	2	125.7	1508.9
$NiCl_2$	59,218	227.6	4	2	129.5	1829.1

Reversible chemical reaction: $\mathrm{Solid}(n+m)NH_3+H \leftrightarrow \mathrm{Solid}\,nNH_3+mNH_3(\mathrm{gas})$.

but also many project cases reported by companies like Beijing SinoRefine Air Conditioning Technology Co., Ltd. [93].

Energy for air dehumidification can be stored efficiently and almost non-dissipative in liquid desiccants system in storage tanks as shown in Fig. 19 [94]. Early in 1992, Laevemann and Sizmann [95] pointed out that salt solutions were suitable for dehumidification due to high storage capacities. Kessling et al. [96] undertook parametric studies on the dehumidification enthalpy storage in a cooled absorber under ARI outdoor conditions (35 °C, 14.5 g/kg, 40% r.h). They also gave the definition of energy storage capacity by desiccant solution as the following equation [97]:

$$S=\frac{(m_{a,\mathrm{in}}d_{a,\mathrm{in}}-m_{a,\mathrm{out}}d_{a,\mathrm{out}})\rho_{s,\mathrm{out}}r}{m_{s,\mathrm{out}}} \quad (1)$$

where r identifies the latent heat of vaporization at the average temperature of desiccant solution in the dehumidifier. Based on the above equation, heat storage capacity is dependent on the moisture removed from air in dehumidifier. Therefore, the energy storage capacity is limited by the mass of moisture removed from desiccant during regeneration process.

In China, Shanghai Jiao Tong University, Tsinghua University, Southeast University and Dalian University of Technology had devoted a lot of work on liquid desiccant system and energy storage. Zhenqin Xiong [98] gave an elaborate analysis on the performance of energy storage of a two stage solar liquid desiccant (LiBr) dehumidification system assisted by $CaCl_2$ solution in her doctoral dissertation. The energy storage density and effectiveness of LiCl was shown in Fig. 20. With the increasing of concentrating difference of LiCl, both the storage density and effectiveness increase.

In the liquid-desiccant dehumidification system, though energy storage can be effective and simply storage by the desiccant solution, the coefficient of the system performance will be lower due to the expense of energy. Besides, the crystallization should also be concerned because of the sensitive affection of temperature for concentrated salt solution.

6.2. Hygroscopic building materials

The conception of Hygroscopic building materials (HBMs) was first mentioned by Nishifuji Miyano and Tanaka [99] and the humidity control material was studied and developed with the usages on textiles, chemistry industry and historic protections. Usually, it was made from minerals, charcoals, silica gels and so on.

Fig. 19. Storage tanks in liquid desiccant system [94].

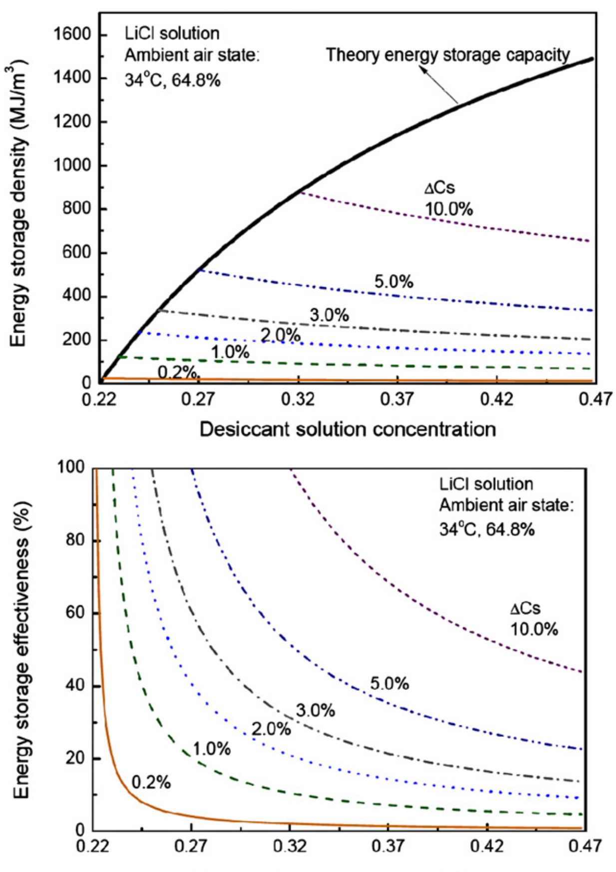

Fig. 20. Energy storage density and effectiveness of LiCl solution under Shanghai summer condition [98].

HBMs or humidity-control materials, as a moisture buffer, is energy costless, easy to handle and be recyclable. In the heating season, direct energy consumption can be saved due to the heat released during the moisture accumulation process in hygroscopic materials, which will decrease the required heating energy. During summer, HBMs can reduce the indoor humidity and consequently reduce the indoor enthalpy. Therefore, the energy consumption of cooling the building decreases while the indoor air quality is improved. HBMs can ameliorate indoor humidity conditions and it is possible to affect the indoor temperature and outdoor ventilation rate and it turns out a similar performance with less energy consumption.

Most researches focused on the characteristics of different HBMs. Huang Jiyi and Jin Zhaofen [100] discussed the feasibility of the HBM as an indoor humidity controlling method under the weather condition in Beijing. They used a super absorbent polymer gel with high molecular weight as HBM and presented the characteristic and feasibility under the estimation of typical humid load in an office. Lei [101] investigated the characteristics of SiO_2-aerogel by using theoretical analysis and experimental method, both the moisture absorption/desorption performance and the dynamic absorption/desorption characteristics of SiO_2–aerogel were studied.

In recent years, a series of studies were devoted to experimental research on transient models of hygroscopic materials, especially in university of Saskatchewan. Olalekan et al. [102] measured the moisture buffering capacity of spruce plywood and the experimental results are compared to a numerical model for validation. Then, another paper [103] completed this research by estimating the effect of hygroscopic materials on energy consumptions in buildings and the results show that with well-controlled HVAC the heating and cooling energy consumption can be reduced by up to 5 and 30%, respectively. In [104–106], Talukdar et al. described the transient moisture transfer facility used to generate the experimental data of HBMs and different materials included cellulose insulation, spruce plywood and gypsum boards. While a series of experiments with different applying parameter have been done by Zhang et al. [107] to quantitatively evaluate the moisture buffering effect by applying HBMs and the conclusion was drew that the effects of moisture adsorption/desorption decreased exponentially when the ambient air change rate per unit area of HBMs increased. Moreover, researches should be further on the application of building in practice to confirm the performance of HBMs.

7. BIPV with energy storage

7.1. Solar battery

In the last decade, the Chinese government has strongly confirmed renewable energy would play an important role in its energy supply and future sustainable development. Therefore, many laws and government policies have been issued to promote development of renewable and sustainable energy, and provide vigorous support to promote its technological progress and applications. The solar energy photoelectric technology is one of the most important choices for the sustainable future and the storage battery system plays a vital role to ensure the continuity and stability of electricity supply. Currently, most commercial buildings have uninterruptible power source (UPS) based on rechargeable battery to provide emergency power for protecting computers, data centers or other important electrical equipment. The rechargeable battery packs can be driven by conventional energy or solar energy.

For a BIPV system, solar panels on the roof play the roles of receiver and convertor. The electricity converted from solar energy can be supplied directly to end-users, or stored in batteries, or to the smart grid, if possible. No matter whether it is possible to be supplied to the grid or not, the batteries system is a crucial part as an energy storage component. There are various types of batteries technologies can be adopted in BIPV system, such as valve regulated lead–acid (VRLA), Lithium-ion (Li-ion), sodium–sulfur (NaS), vanadium redox flow battery (VRB), electric double-layer capacitors (EDLCs), etc.

The lead–acid battery is the most widely choice for PV storage systems along the world due to the advantages of low cost, good performance and wide availability, and the rapid development of the PV industry is increasing demand for lead–acid batteries. More than three fourth of the PV/wind power system use this kind technology. Chang et al. [108] concluded that there are huge potential for the PV market in China in the future because of the encouragement of Chinese government and society and the valve-regulated lead–acid (VRLA) batteries will be the most practical candidate for the BIPV energy storage application.

VRB was first developed by Skyllas–Kazacos and co-workers in the University of New South Wales, Australia in 1984 [109–111]. Compared with lead acid battery or other battery, VRB is much practical and promising because of higher energy efficiency, longer operation life and lower cost, though there are still many bottlenecks that need to be broken, such as electrode materials, membrane and bipolar plate [112]. Lots of universities and institutes in China, such as Central South University, Tsinghua University, Northeaster University, and Institute of Metal Research Chinese Academy of Science and Dalian Institute of Chemical Physics have engaged in the development of VRB. Since the vanadium resources are rich in China, promoting VRB system can not only improve the energy utilization efficiency, but also ameliorate environment and utilization of resource.

Sodium–sulfur battery is also one of the most promising candidates for electricity storage, and provides value via energy arbitrage and voltage regulation. Great developments have been achieved during the last two decades, especially under the collaboration of Tokyo Electric Power Company and NGK Insulator, Ltd. However, in China good quality beta-alumina ceramic tubes of different sizes were prepared and fabricated by the Shanghai Institute of Ceramics, Chinese Academy of Sciences for energy storage [113]. The kind of cell showed a good performance of cycling stability and reversibility. Because of the operating temperatures and the corrosive characteristic of sodium polysulfides, this kind of cell is suitable for grid energy storage and some trial projects have already been shown. Presidio, Texas town built the world's largest NaS battery to provide up to eight hours power supply when the city's lone line to the power grid goes down [114].

7.2. Grid-connected BIPV system

The power grid can be seen as an infinitely great and infinite cycle life battery for BIPV system, and the grid-connection of PV panels to a utility grid can eliminate the need for batteries and associated accessories.

Currently, China is the biggest manufacturer and supplier of solar PV panel in the world by providing more than half of the whole world's solar PV panels. The Chinese government announced a subsidy program for BIPV projects in March 2009 and "the Golden Sun Demonstration Project" aiming at supporting the development of PV electricity generation ventures and the commercialization of PV technology in China. However, large-scale PV power for domestic utilization has been showed too expensive and approximately 98% of PV products are destined for overseas markets [120].

The government set on-grid tariffs for newly grid-connected solar power stations in northwest of China at 1.15 RMB/(kW h) ($ 0.18/(kW h)) in early 2010, because of the fast development of the solar manufacturing industry, while the bidding for a 10 MW project resulted in a price of 1.09 RMB/(kW h) in Dunhuang, Gansu Province. Compared with the on-grid electricity tariffs of coal-fired power plants (0.4–0.5 RMB/(kW h)) and the tariffs for hydropower (0.2–0.3 RMB/(kW h)), the tariffs of grid-connected solar power were still less competitive. With the increasing price of energy, this value will be feasible for the market soon.

The following results on the operation of the first grid-connected BIPV system in Hong Kong had been reported by Yang et al. [121]. Li et al. [122] studied a grid-connected PV system installed in an institutional building. By experiment data, they calculated the monetary payback period was 72.4 years when the electricity-buying price is equal to the electricity-selling price, while the embodied energy payback period was about 9 years.

In China, the monopoly control of the civil power grid by local power companies is one of the biggest obstacles for the application of grid-connected system. Under these circumstances, the grid-connected BIPV systems require the agreement of local power companies and the application of smart power grid. Though the grid-connected BIPV application does not show a good economical feasibility in China until now due to the low efficiency and high initial investment, this technology should still be promoted because of its advantages of environmental protection and energy saving for sustainable development and great potential in the future, and also for the smart power grid.

7.3. PV-Trombe wall

Many theoretical and experimental studies have shown that indoor thermal comfort was improved due to well-designed Trombe walls. However, its wide application was restricted due to less function and unaesthetic layout. PV-Trombe wall (PV-TW) is a novel Trombe-wall with PV panels, which can convert solar radiation into electricity and store the heat at the same time.

By theoretically and experimentally methods, Ji et al. [123] investigated the PV-TW wall installed in a fenestrated room with heat storage, considering both fenestration and heat storage. The schematic diagram of PV-Trombe wall was shown in Fig. 21. The testing results showed that a significant indoor temperature increase can be obtained, meanwhile the daily electrical efficiency of the PV-TW can reached 10.4%. Sun et al. [124] established a testing system with a PV-TW and a window used on the south façade of a hot box (as shown in Fig. 22), whereas a dynamic numerical modeling was developed. The effect of PV coverage and the influence of a southern facing window on the PV-TW were studied.

8. Examples and commercial cases with building integrated energy storage

8.1. Solar water tank for adsorption chiller

A solar adsorption cooling system with heat storage was designed by Zhai and Wang [125] and applied in the green

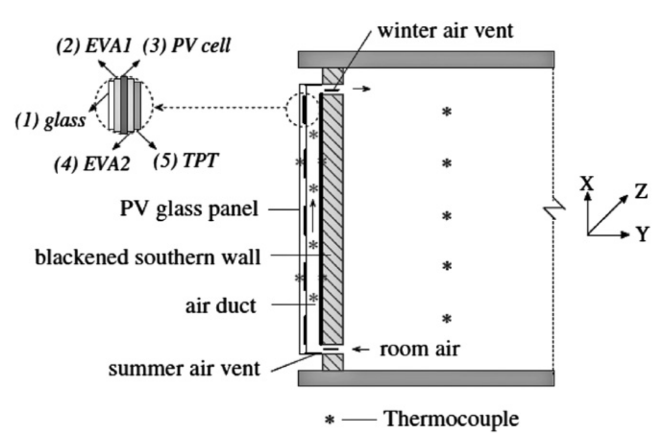

Fig. 21. Schematic diagram of PV-Trombe wall for winter heating [123].

building of Shanghai Research Institute of Building Science. A heat storage water tank plays the role of reservoir and re-distributor to connect the solar collector circulation and the hot water circulation (as shown in Figs. 23 and 24). A 2.5 m^3 thermal storage tank was integrated in the solar cooling system. Solar energy was collected by 90 m^2 of evacuated tubular solar collectors with CPC installed on the south west side of the roof, while another 60 m^2 of heat pipe evacuated tubular solar collectors installed on the southeast side. They concluded that the system was stably due to regulating effect of the heat storage water tank. They also suggested that in areas with rich resources of solar energy the system without heat storage is much more suitable, considering no water pump and less whole power consumption was needed.

Fig. 22. South façade of the hot box equipped with PV-TW and window [124].

Fig. 23. Integration of the solar collector array and the green building [125]. (For interpretation of the references to color in this figure legend, the reader is reffered to the web version of this article.)

8.2. Application of pebble bed energy storage system for space heating

The system (as shown in Fig. 25) was applied to heat a 3320 m^2 indoor area in Qinhuangdao as the first large scale practical solar air heating system in China as mentioned before [48]. As shown in Fig. 26, during the charging stages, the temperature of pebble bed increased during the day, while at night the temperature decreased to 10–12 °C without heating. The pebble bed was designed to preheat for days before the heating season coming.

They chose three rooms to compare different heating strategies, Room A (traditional central heating), Room B (solar heating system with pebble bed), and Room C (without heating supply). The result is presented in Fig. 27 and the temperature fluctuations of room A and B were affected by human activities, while in room C the temperature was much stable. The indoor temperature of room B obtained more than 11 °C during the night and the temperature difference between indoor and outdoor was up to 20 °C (Tables 4 and 5).

8.3. Composite PCM for hot water supply

The low thermal conductivity of PCM makes heat storage/retrieval rates lower and becomes one of the biggest bottlenecks in application. Zhang et al. [126] studied the performance of a shell and tube LTES system, which used the expanded graphite to

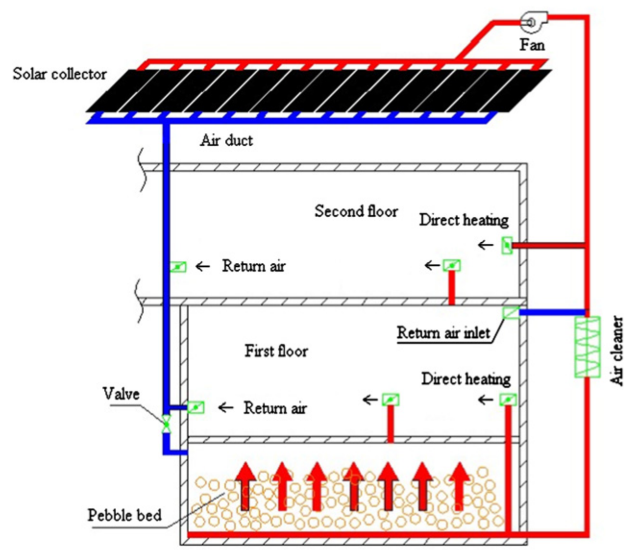

Fig. 25. Schematic diagram of the solar energy storage system [48].

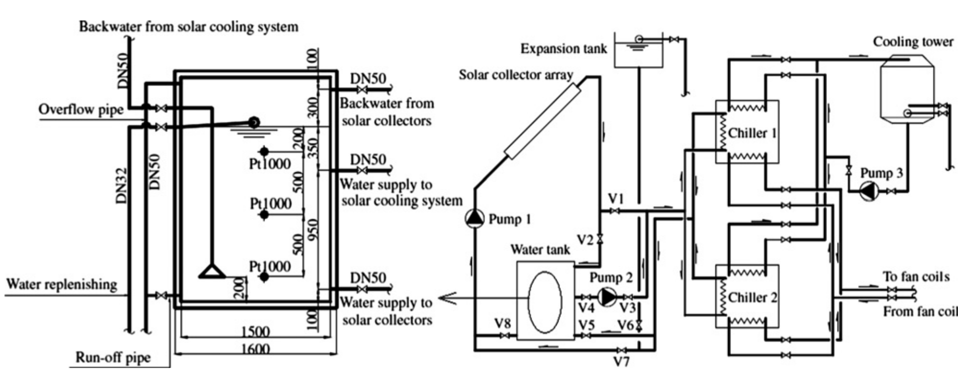

Fig. 24. Schematic of water tank and solar-powered adsorption cooling system [125].

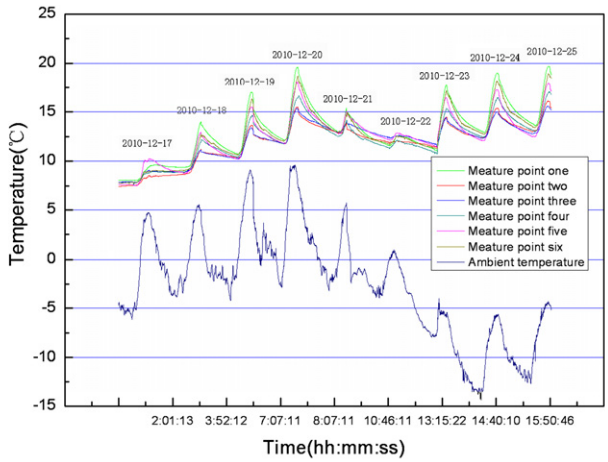

Fig. 26. Temperature variation of the storage bed during the charging stages [48].

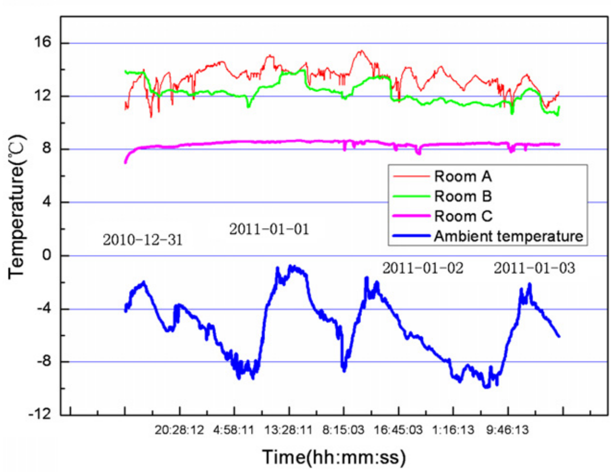

Fig. 27. Temperature variation in different types of heating room [48].

Table 4
Properties of some batteries [115–118].

Type	Energy density (W h/kg)	Efficiency (%)	Cycle times	Life (years)
Lead–acid	30–40	50–92	500–1200	20 (stationary)
Li-ion	150–250	80-90	1,200	2–5
NaS	150	89–92	2,500	15 (stationary)
VRB	25–35	80	14,000	10–20 (stationary)
EDLCs	0.5–30	95	Millions	10

enhance the thermal conductivity, built for room heating and hot water supply in a family. The PCM was technical grade paraffin with the purity of 99% and a melting temperature of 62 °C, and the EG/paraffin composite with 7% mass fraction of EG was used. The schematic diagram of the experimental apparatus was shown in Fig. 28. The LTES tank, which was insulated with thermal insulation material of 50 mm in thickness, had a capacity of 166 L. In this tank, 27 heat storage tubes with the 76 mm in inner diameter and 750 mm in height were uniformly packed and supported by a wire mesh. The experimental results showed that the utilization of paraffin/EG composite PCM greatly enhanced the heat storage/retrieval rates of the LTES system (as shown in Fig. 29). Under the operation condition, the LTES system with composite PCM showed a 44% reduction in heat storage duration and a nearly 69% reduction in the retrieval duration, compared to those for pure paraffin.

8.4. Solar battery utilization for countryside

In China, a shortage of electricity is very normal in remote areas like Qinghai-Tibet Plateau, because of their geography position and undeveloped economic. Nevertheless, the solar resource is abundant in these places. In Tibet, the total annual solar insolation and the annual average hours of sunshine are easily up to 8000 MJ/m^2 and 3000 h, respectively. Under this circumstance, Tibet has the highest utilization rate of solar energy in China. A number of stand-alone PV power stations are built for household electricity generation in these remote counties.

Hua et al. [127] introduced an application of VRLA batteries to stand-alone PV system in northwest of China. The solar array and the VRLA batteries are presented in Figs. 30 and 31 individually. The PV power station includes a solar array, a set of control equipment, and a battery pack with four strings of 110 units of 2 V 600 A h VRLA batteries, which connected in parallel. The batteries were working under daily cycling: the battery packs can be recharged during the day and discharged during the night. The authors have record the discharge data of the batteries from 19 January to 6 November in 2003. And the batteries supplied average electrical power of 23.9 kW h every day, which lasted about 5 h. The battery storage system can work steady for more than 6 years based on the present operational state and the test results in laboratory. With the improvement of storage performance and the price reduction, the solar battery would have a more widely used application.

8.5. A grid-connected BIPV system in Hong Kong

As mentioned before, Yang et al. [121] introduced the first grid-connected BIPV system in Hong Kong. The 100 PV panels with each 80 W_p were installed on the vertical east (20 panels), west (22) and south (18) façade and the horizontal roof (40) of a plant room on a building. The system was rated at 8 kW with output dc voltage of 75–105 V, output ac voltage of 220 V. The photo and schematic diagram are shown in Figs. 32 and 33. Compared to the local civil electricity average price (about HK$ 0.90/(kW h)), the on-grid tariff of the BIPV system was found to be about two times (HK$ 1.5–2.0/(kW h)). This pilot demonstration work plays an important role in the future development of sustainable energy application in Hong Kong, thought the economic feasibility still need to be reconsidered due to the payback seemed to be more than 20 years.

8.6. Commercial application of building integrated energy storage

Compared to SHS, LTES has high storage density, nearly isothermal characteristic of the storage and release process undergoing the phase changing. It is becoming much more promising for space heating and cooling in buildings. Currently, many PCMs company can provide varies PCMs products for commercial projects, such as Cristopia Energy System in French [128], Phase Change Material Products Limited in UK [129], Phase Change Energy Solutions in USA [130], RUBITHERM in Germany [131] and so on.

The French company, Cristopia Energy System, have reported many latent energy storage projects around the world, included Asia World-Expo in Hong Kong in China [128]. The STL is composed of a tank(s) filled with nodules and heat transfer fluid. The spherical nodules are blow molded from a proprietary blend of polyolefin and filled with PCM, while the heat transfer fluid is usually mono-ethylene glycol. By using this system, the installed

Table 5
Advantages and disadvantages of different batteries [108,115–119].

Type	Advantages	Disadvantage
VRLA	Simple operation and maintenance free Minimal leakage Small footprint and flexible installation Low cost	Short cycle life Heavy Poor performance at high/low temperature Sulphation
Li-ion	Wide variety of shapes and sizes Environmentally safety Much lighter than other secondary batteries High open circuit voltage	Capacity loss by high charge levels and elevated temperatures Short lifetime Need multiple protection Intolerance of overcharge and over discharge
NaS	High energy density High current, high power discharge High efficiency of charge/discharge Fabricated from inexpensive materials	High operation temperature of 300–350 °C Highly corrosive nature of the sodium polysulfide
VRB	Large capacity Rapid response Long operation life and low cost Deep charge/discharge cycles possible	Big in volume Solid deposition of vanadium metal in felts if charge rates too high
EDLCs	Long life and high number of charge–discharge cycles High cycle efficiency High output power Simple charge methods	Generally low energy density for a standard ultracapacitor High self-discharge Low maximum voltage The voltage across EDLCs drops significantly

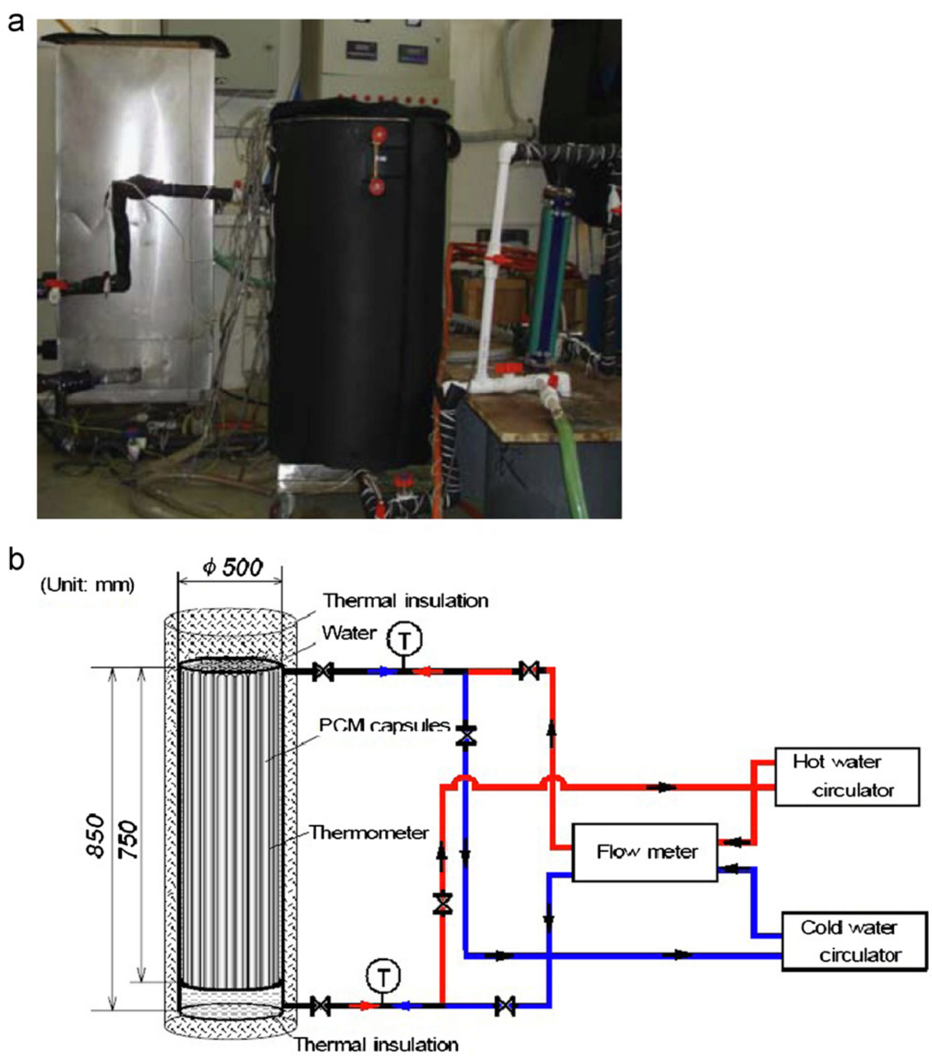

Fig. 28. Experimental setup of LTES system (a) photographic view (b) schematic [126].

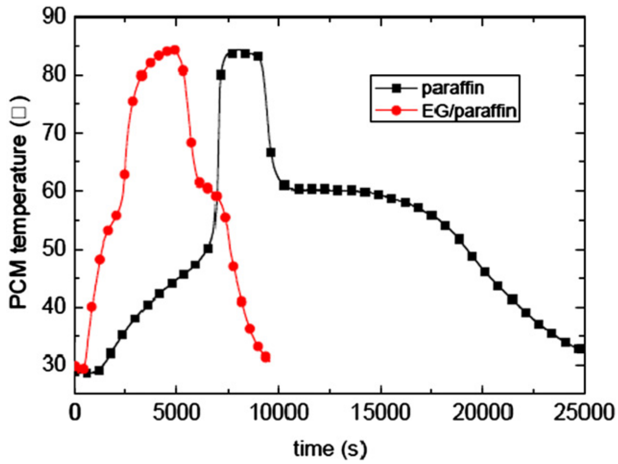

Fig. 29. Temperature evolutions of the LTES unit with pure paraffin and EG/paraffin composite during heat storage and retrieval circle [126].

Fig. 30. Photo of 20 kW PV power station in Zheng Qi County, Tibet [127].

Fig. 31. VRLA batteries in battery room [127].

chiller capacity can be significantly reduced about 50%. The STL TES system provides the shortfall of the energy when demand is higher than the chiller capacity. Thus chiller can operate continuously under a maximum efficiency. The technical data and load profile about the Asia World-Expo project were shown in Table 6 and Fig. 34, respectively.

For the company Phase Change Material Products Limited [129], a lot of building temperature control applications had been realized. The PCM energy storage extends the operation periods of a CHP and successfully applied for the National Theatre site in London. For this building, all three services included electricity, cooling and heating are needed all year round. Rather than shutting down the CHP system by adding PCM energy storage

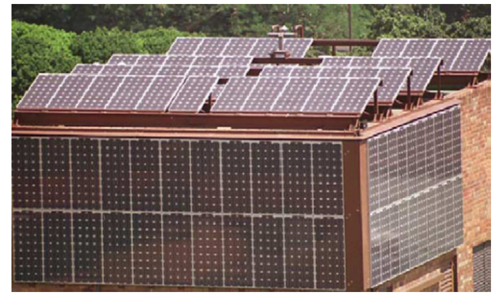

Fig. 32. The photo of first grid-connected BIPV system in Hong Kong [121].

for cooling (2000 kW h) simply, it can either use the surplus energy storage while providing the required heat or electricity output. Another project was zero energy office building in Malaysia [129] (Fig. 35). As shown in Fig. 36, the cool PCM storage was used to shift the cooling load for daytime to nighttime for Malaysian ambient conditions. The gross floor area of this office building is 4000 m^2, while the year energy index is 35 kW h/m^2 excluded PV. For the PCM storage tank, the melting point is 10 °C and total storage capacity is 580 kW h and is charged with 7 °C water during night time.

Qatar has win the bid of FIFA 2022 World cup and a full scale demonstration stadium using solar energy to drive air conditioning using PCM-based TES system [129,132]. As shown in Fig. 37, the double-effect lithium bromide absorption chiller is driven by Fresnel solar collectors out the stadium. To enable the solar-powered chiller's output to be stored until it is needed in the evening, the cooling capacity is stored in the PCMs storage tank with PCMs freezes at 6 °C. And under fully charged situation, the PCM storage tank can provide up to 5 h of cooling for the whole stadium. In addition, a giant PV installation is designed, located adjacent to the Fresnel reflectors on the stadium's solar farm. As a zero carbon and environmentally friendly design, the showcase stadium is important for the next step of applying the low carbon technologies including PCM-based storage into the giant football stadiums planned for the World Cup.

Though there are a few commercial PCM companies and commercial applications in China, the energy storage opportunity of benefits for building operations is huge. Generally, the advanced energy storage markets are still in pre-commercialized stage and the cost of energy storage devices is expected to decrease over the next decade with the improvement of PCM properties and system design.

9. Conclusion and perspective

A review of energy storage technologies and development, which can be integrated with buildings, has been carried out. This paper includes six parts: thermal energy storage materials, sensible heat storage, latent heat storage, thermochemical energy storage opportunity, energy storage in desiccant system and storage in BIPV system. Various demonstration projects for buildings had been introduced including solar water tank with or without PCMs, solar packed bed storage system, Chinese kang, latent heat storage system like PCMs applied in different kinds of building envelope and ice-based or PCM-based TES in commercial projects. There are several kinds of energy storage systems, which should pay much more attention and might be feasible for buildings.

1. Solar water tank storage system has been maturated and wildly used. Especially in the country, solar water tank can be used to provide 45–70 °C hot water for bathing, laundry and

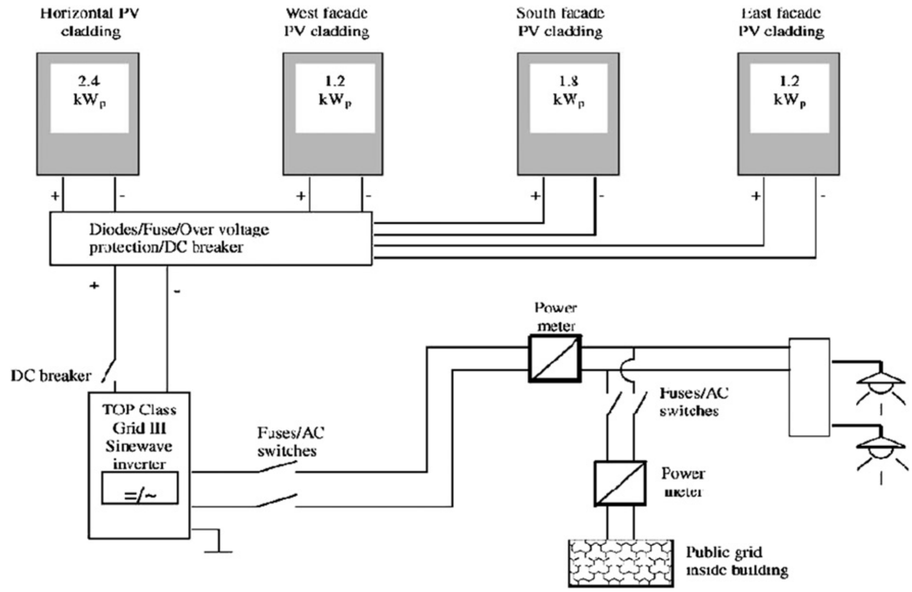

Fig. 33. Schematic of the grid-connected BIPV control system [121].

Table 6
Technical data for Asia World-Expo project [128].

Peak cooling load	25 MW
Air cooled chiller	9 × 1,100 kW (40%)
STL capacity	15 MW (60%)
Storage capacity	75,000 kW h
Storage volume	1,404 m^3

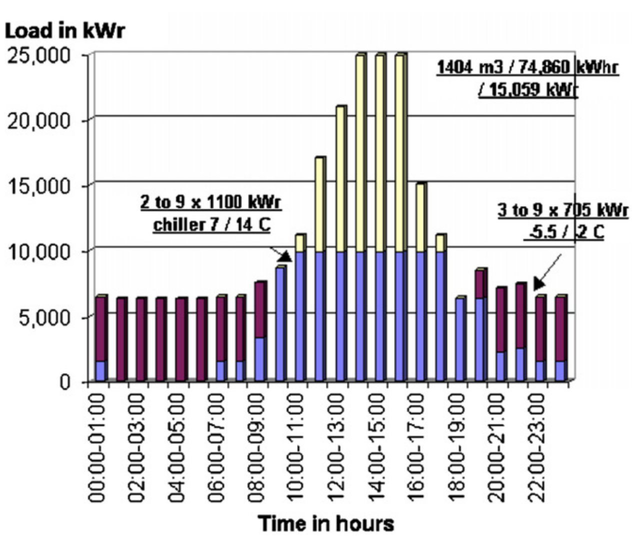

Fig. 34. Load profile for Asia World-Expo project [128].

Fig. 35. Photo of zero energy office building in Malaysia [129].

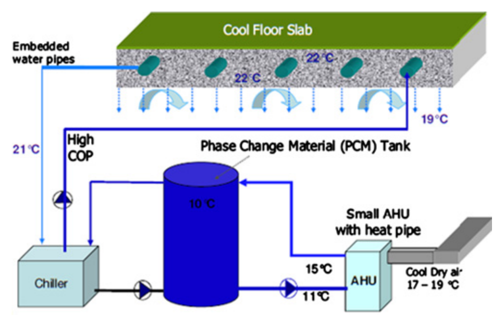

Fig. 36. Cooling storage in floor slab and PCM tank [129].

Fig. 37. Doha FIFA 2022 World cup stadium [132].

so on. In the city, the horizontally partitioned water tank can be placed in a limited room like attic or basement. Water tank can also provide 70–80 °C hot water for adsorption chiller during the summer day and the water temperature can be much stable. In addition, the water heating storage system combined PCMs modules can improve the storage density and capacity.

2. PCMs system for building envelopes can be applied for both passive and active energy storage by different system designs. For passive building energy storage, the suitable phase change temperatures range from 18 to 28 °C and the SSPCM make the application feasible and promising. For active storage system, the design is much complicated and the off-peak electricity is highly recommended to be used for buildings, which have regular daily heating/cooling loads in the city like office

building. The properties of the PCMs play the vital role, including the phase change temperature, latent heat of fusion, conductivity, cost and so on. Considering these features, the Paraffin with many advantages might be one of the most promising PCMs. Furthermore the paraffin composites with EG can provide high thermal conductivity. However, the study on searching and creating novel PCMs with better performance and suitability for buildings should never stop.
3. Though thermochemical energy storage has been rarely applied in practical projects, this kind of storage still has a great potential with high storage density and simple operation.
4. For liquid desiccant energy storage system, a solution tank for storage is needed and much attention should be paid on the energy storage capacity of the salt solution. The liquid desiccant energy storage driven by solar energy or off-peak electricity makes itself more attractive and competitive, though this kind of system has not been totally accepted by the market due to high first cost, corrosive and uncertainty of the influence of the salt solution.
5. The BIPV system with storage component (battery packs) may supply a stable and continuous power and even during the night. NaS battery can be the most competitive candidate for application to support the electric grid. With the subsidy from government and the decreasing of the tariffs and initial cost of grid-connected solar power, the BIPV system with energy storage would be more feasible.
6. As mentioned above, comparisons can be made between all these different storage methods. For commercial applications, the main choices include the UPS with rechargeable battery packs and TES with PCMs for storage cooling energy during the night. As shown in some previous demonstrate projects provided by different PCM companies, the buildings can use conventional energy during off-peak time or renewable energy source to make ice, which then exports cooling power during peak time. Though, as an energy efficient choice, PCM-based storage provides other benefits of reliable operation, increased capacity and flexibility system. However, if the purpose is lowering the building's carbon footprint, then renewable energy source need to be take into consideration to drive the chillers for storing cooling. However, several issues have limited market penetration of TES systems. For the initial cost of PCM-based TES is usually higher than adding chiller capacity. Moreover, a lack of experience with design and running the TES system may lower the system efficiency.

A significant technical progress on the building integrated energy storage has been made during these last decades, especially on the PCMs application integrated with building. Currently, as one of the most promising ways for practical engineering application integrated with building, several forms of encapsulated PCMs (both micro and macro encapsulation methods) are developed and marketed for both active and passive applications. For the thermo chemical storage, sorption reactions are very attractive, but still need more research investigation on system design before it can be used widely in commercial projects. The performance of rechargeable batteries are improved a lot including the cycles times and efficiency. With the interest increased on smart-grid technologies and government's supports, grid-connected BIPV system deserves a rapid development.

In this paper, both the advantages and disadvantages of each application had been discussed. Building integrated energy storage in China will have a brilliant future, though problems such as heat transfer enhancement of heat storage mediums, performance attenuation for long term application, safety of fire rating of storage system, combination with active solar system, financial feasibility etc. still need to be focused on and carefully designed in the future application. More demonstrate projects integrated energy storage systems should be built to show how to apply these technologies into practice and provoke interest in energy storage in buildings.

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